Completion of 400 kV Pre-qualification Test for DC-XLPE Cable System

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ABSTRACT

The HVDC cross-linked polyethylene (DC-XLPE) cable we developed has excellent properties under DC voltage application, especially a very low accumulation of space charge. These DC properties are due to our special technique used for the XLPE insulation material. Our DC-XLPE cable can be applied to DC link lines with not only Voltage Source Converter (VSC) technology but also Line Commutated Converter (LCC) technology with polarity reversal operation in temperatures of up to 90℃, which is conductor temperature. In order to qualify the HVDC cable systems with LCC at an operating temperature of 90°C pre-qualification (PQ) testing was conducted in accordance with the test conditions of CIGRE Technical Brochure 496. In this paper, the fundamental properties of the DC-XLPE insulating material will be reviewed and the PQ testing results of the 400 kV DC-XLPE cable system will be described.

KEYWORDS

DC cable, Cross-linked polyethylene, PQ test, CIGRE Technical Brochure 496.

INTRODUCTION

Around the world, the main application of HVDC power transmission has been aimed for long-distance power transmission such as intercontinental links. However, in recent years, there has been a growing trend toward its application to offshore wind power generation, which is being actively introduced in Europe as a renewable natural energy resource. As its introduction has progressed, the locations of the wind power generation facilities have been shifted from coastal areas to offshore areas due to space constraints. As the power transmission distance has increased, HVDC power transmission technology has drawn more attention.

Previously oil-impregnated insulation cables, such as mass impregnated (MI) cable and oil-filled (OF) cable, have been applied to DC power transmission. In recent years, however, because of the increasing awareness of environmental protection, extruded insulation cables have come to be desired as the oil-impregnated insulation pose on risk of oil leakage.

On the other hand, cross-linked polyethylene (hereafter, AC-XLPE) insulation cable, which is currently widely applied to AC power transmission, is known to have a number of problems in insulation when used for DC usage, i.e., prominent accumulation of space charge in AC-XLPE insulation material. Therefore, we have developed a DC-XLPE insulation material that has excellent DC characteristics. We have also developed a DC-XLPE cable using the above mentioned material as an insulation. This paper describes the excellent DC characteristics of the DC-XLPE insulation material developed for DC applications, and reports on the implementation status of the PQ tests in accordance with CIGRE Technical Brochure on actual cables and accessories of the 400 kV DC-XLPE cable system.

DC CHARACTERISTICS OF DC-XLPE INSULATION MATERIAL

AC-XLPE insulation material exhibits excellent insulation performance for AC voltages, but it does not exhibit adequate performance for DC voltages due to multiple reasons such as the accumulation of space charge. By adding inorganic fillers in the XLPE insulation, an excellent characteristic can be obtained. The DC-XLPE insulation material for DC usage, to which inorganic fillers have been added, has the following features in comparison with AC-XLPE:

- High volume resistivity
- Low space charge accumulation
- Long DC life time
- High DC breakdown strength

We will show these characteristics of DC-XLPE in comparison with AC-XLPE. It has been found that DC characteristics are susceptible to the crosslinking by-products. AC-XLPE, which was dried at 80℃ in vacuum (hereafter, AC-XLPE (Dry)) was compared in some parts of test.

Volume resistivity

The volume resistivities of DC-XLPE, AC-XLPE and AC-XLPE (Dry) were investigated using sheet specimens formed by press work. The sheet thickness was made to be about 200 µm. The volume resistivity was evaluated with the DC leakage current value measured ten minutes after the measurement was begun. The temperatures were set at 30℃, 60℃ and 90℃, and the electric f ields were set at 40 kV/mm, 60 kV/mm and 80 kV/mm.

The measured volume resistivities are shown in Figs.1 and 2. Fig.1 shows the dependence of volume resistivity on the electric field and Fig.2 shows the dependence on the temperature. As shown in Figs.1 and 2, within the range of the measurement temperature and electric field, DC-XLPE possesses about 100 times higher volume resistivity than AC-XLPE, and about 10 times higher volume resistivity than AC-XLPE (Dry).

Space charge characteristics

The space charge distributions in DC-XLPE, AC-XLPE and AC-XLPE (Dry) were evaluated using the pulsed electro-acoustic (PEA) method. The calibration of the PEA method is recommended by IEC/TS 62758[1]. Pressed sheet specimens with a thickness of about 200-300 µm were used DC voltages with average electric field of 50 kV/mm for the measurement. When we consider long term reliability, it is important that the space charge

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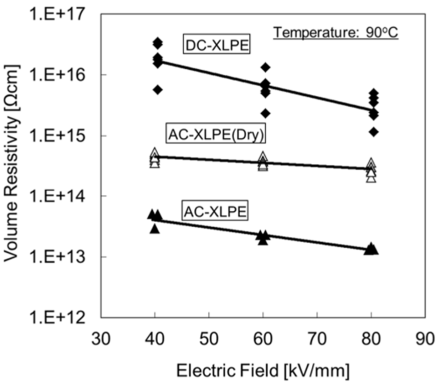


Fig.1: Electric Field dependence of the volume resistivity

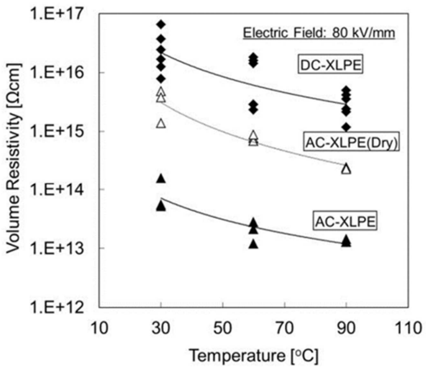


Fig.2: Temperature dependence of the volume resistivity

distribution is uniform and there is no accumulation of space charge. In this case, the long term space charge characteristics were evaluated at 50 kV/mm, which was approx. 2 times larger than the operating electrical field.

Fig.3 and Fig.4 show the time dependence of the space charge distributions and the electric field distribution of DC-XLPE, AC-XLPE (Dry) and AC-XLPE when a DC voltage of 50 kV/mm was applied. For DC-XLPE as shown in Fig.3 (a), a space charge was not accumulated inside the specimen, and the result hardly changed after 7 days. As shown in Fig.4 (a), the electrical field distribution of DC-XLPE is nearly uniform, hardly changed from the uniform electrical field 50 kV/mm and is not influenced by time. For AC-XLPE (Dry), shown in Fig.3 (b), a space charge was seldom accumulated until after 60 min. Fig.4 (b) shows the electrical field distribution of AC-XLPE (Dry) which is nearly uniform after 60 min. However, a negative space charge was accumulated in AC-XLPE (Dry) after 1 day and 7 days. The electrical field distribution of AC-XLPE (Dry) was warped by the influence of the negative space charge. For AC-XLPE, Fig.3 (c) shows a space charge was definitely accumulated after 60 min. The space charge distribution of AC-XLPE changes gradually with the progress of time. Fig.4 (c) shows the electrical field distribution of AC-XLPE was definitely warped by the influence of the space charge accumulation. The electrical field distribution of AC-XLPE changes with time. Thus, the time dependences of space charge distribution and electrical field distribution differ in every material.

In order to numerically express the effect of space charge on the electric field in a concrete manner, we obtained the field enhancement factor (FEF) as defined below by Equation [1] and evaluated its change over time:

$$\text{FEF}=\frac{\text{Maximum electric field in specimen[kV/mm]}}{\text{Applied Voltage[kV]/Thickness of specimen[mm]}} \quad [1]$$

Fig.5 shows time dependence of FEF in DC-XLPE, AC-XLPE (Dry) and AC-XLPE. The FEF in DC-XLPE rises slightly for an early short period of time, but is found to be stable and remain less than 1.1 for 7 days from the beginning. The time dependent change of DC-XLPE is small. The FEF in AC-XLPE (Dry) has a slight change after half a day. After that, it has a rising trend. The FEF of AC-XLPE (Dry) exceeds 1.1 after 2 days, and has an upward tendency for 7 days. The FEF in AC-XLPE has a peak of more than 1.4 after 2 hours. After that, it has a falling trend and is found to be stable. The stable value of FEF is 1.2, which is larger than that of DC-XLPE. The time dependence of the space charge distribution of each material has a different trend. This shows the space charge was accumulated by the influence of the crosslinking by-products. After the FEF of AC-XLPE showed a peak, it decreased and became almost equal to that of AC-XLPE (Dry). It is thought the decreasing of the space charge is caused by volatilization of the crosslinking by-products in AC-XLPE, which is a thin film sample. In DC-XLPE, the amount of the accumulation of the space charge and the influence of time dependence is small. In AC-XLPE (Dry) the carrier source of the space charge accumulation is a carrier that is not removed by vacuum drying at 80℃ for 3 days. For example, so-called additives such as antioxidants and impurities are carriers.

We think the inorganic fillers that are added in DC-XLPE have a good effect on trapping not only the crosslinking by-products but also all other carrier sources.

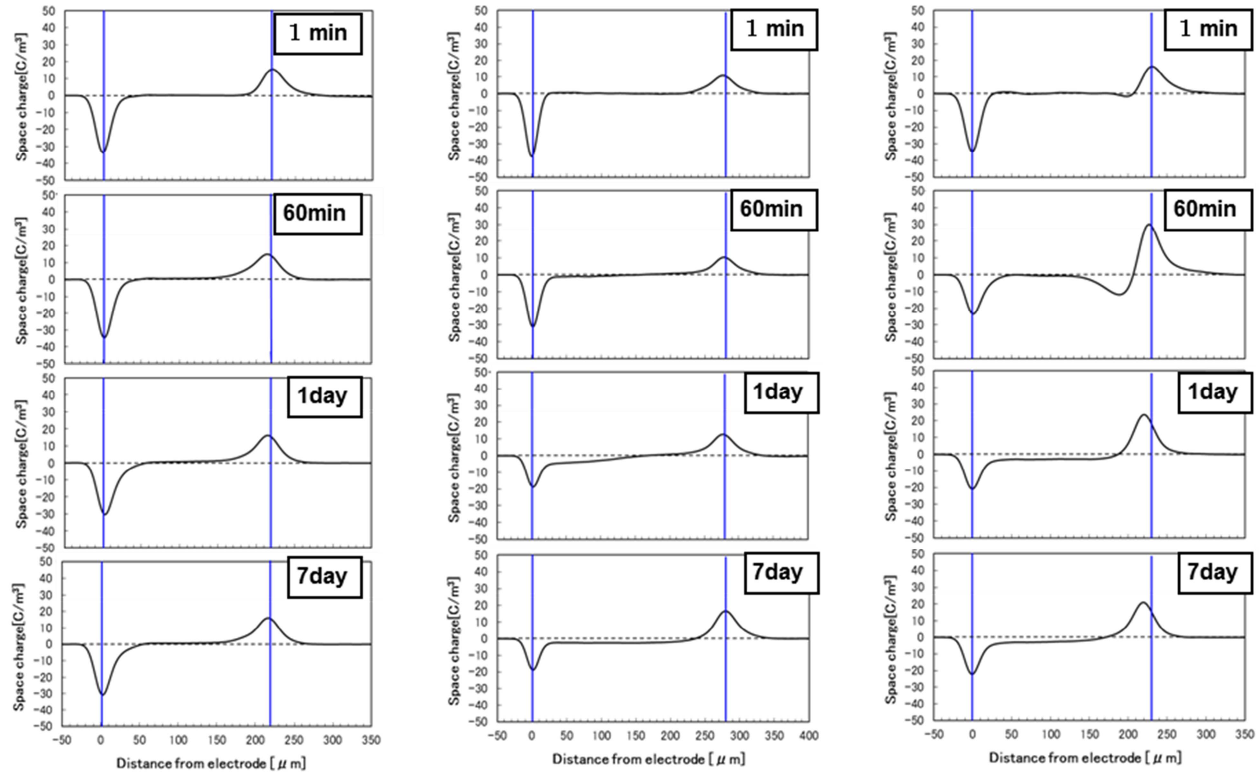
DC V-t characteristics

The DC Voltage-time (V-t) characteristics of DC-XLPE and AC-XLPE were investigated on pressed sheet specimens with a thickness of about 200 μm. A vacuum drying treatment was applied to the AC-XLPE sheet samples to reduce the crosslinking by-products since they were known to affect the space charge characteristics as described in section “Space charge characteristics”. On the other hand, no such treatment was given to the DC-XLPE specimens.

The effective portion of the electrode diameter was 25 mm. The sheet specimens were placed between the high voltage electrode and the ground electrode, and a DC voltage was applied in the silicone oil. Then evaluation was made for the time required for the breakdown. The test was conducted at 90℃.

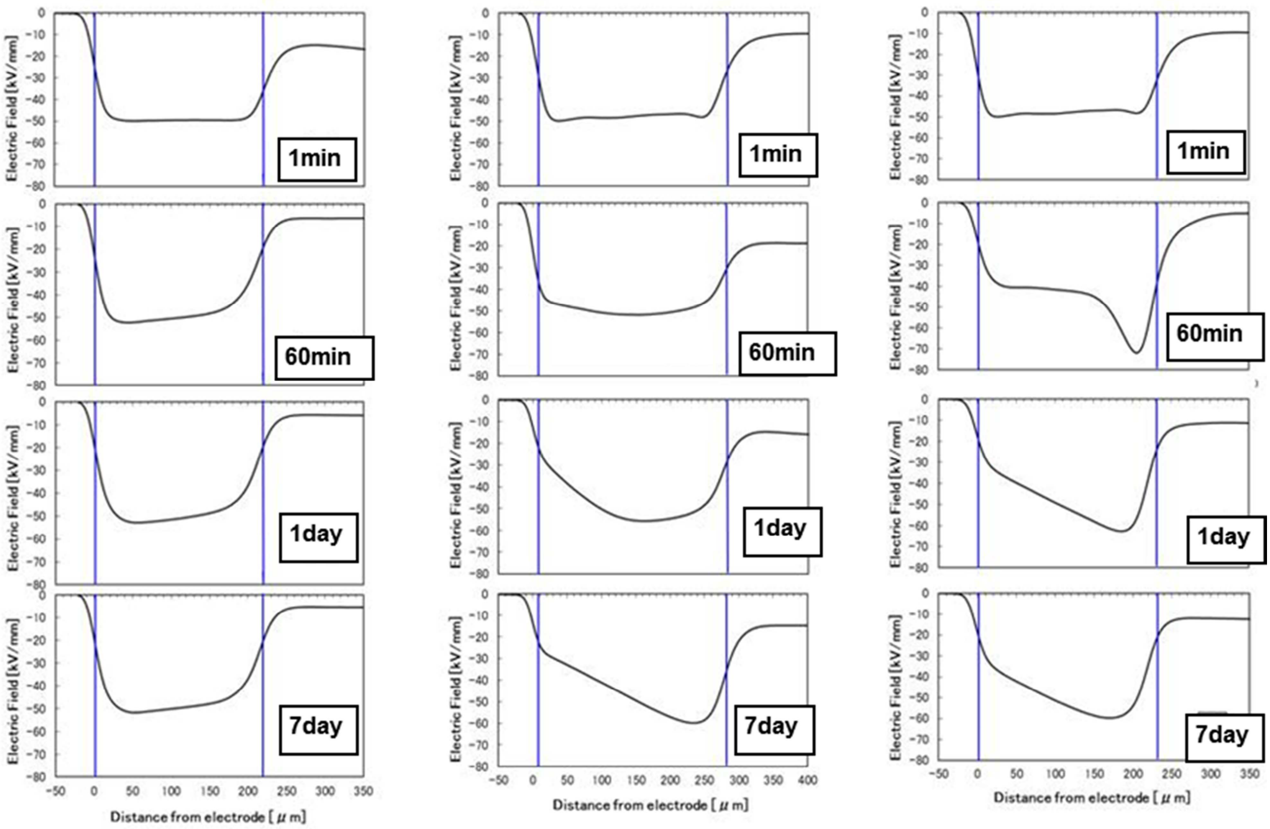
Fig.6 shows the DC V-t characteristics of DC-XLPE and AC-XLPE. In this figure, the vertical axis shows the average electric field, E_{mean}, which was calculated by dividing the applied voltage by the thickness of the specimen. As shown in Fig.6, both cases show a long breakdown time and low stress, and DC-XLPE has a higher DC breakdown strength and longer life time than AC-XLPE.

Assuming that the relationship of Equation [2] is satisfied between the time to breakdown “t” and the electric field



(a) DC-XLPE (b) AC-XLPE (Dry) (c) AC-XLPE

Fig.3: The time dependence of space charge distributions at 50 kV/mm, 30°C



(a) DC-XLPE (b) AC-XLPE (Dry) (c) AC-XLPE

Fig.4: The time-dependence of electric field distributions at 50 kV/mm, 30°C

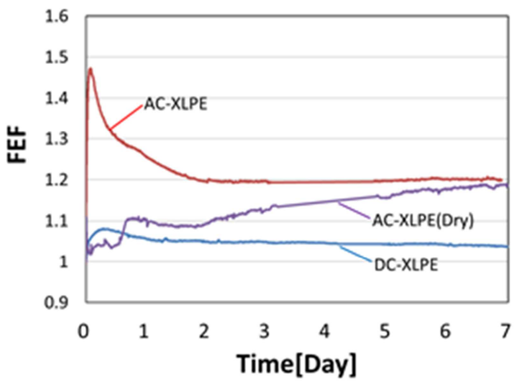


Fig.5: Time dependence of FEF at 50 kV/mm, 30℃

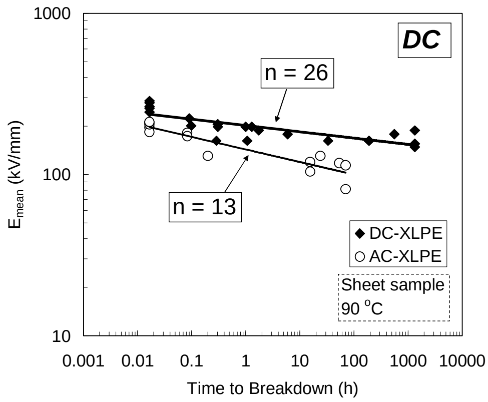


Fig.6: DC V-t characteristics of DC-XLPE and AC-XLPE at 90℃

"E_{mean}," the life exponent "n" can be evaluated.

$$(E_{mean})^n \times t = \text{const.} \qquad [2]$$

As a result, the life exponent "n" is calculated to be 26 for DC-XLPE and 13 for AC-XLPE, showing that the life characteristics of DC-XLPE under DC voltage are improved as inorganic fillers are added.

DC breakdown strength of model cables

We made model cables that have a 9 mm insulation made of the DC-XLPE insulating material. The conductor size of the model cables was 200 mm^2. The model cables were subjected to DC breakdown tests at 90℃.

Fig.7 shows the breakdown strengths of the DC-XLPE cables[2] and our previous data for AC-XLPE cables[3]. The DC breakdown strength of DC-XLPE cable is more than twice that of AC-XLPE cable.

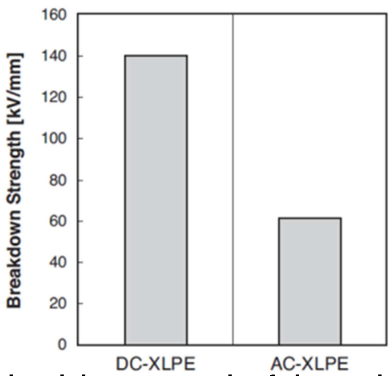


Fig.7: DC breakdown strength of the model cable at 90℃

PQ TEST OF 400 kV DC-XLPE CABLE SYSTEM

Table 1 summarizes the results of the long-term demonstration tests. This section details the PQ testing of the 400 kV DC-XLPE cable systems.

The conductor size was 1,000 mm^2, assuming a power transmission capacity in bi-pole mode of 1,000 MW. The thickness of the insulation was 19 mm. The 400 kV DC-XLPE cables and accessories were manufactured and subjected to a PQ test. Fig.8 shows a photograph of the 400 kV DC-XLPE cable. The conductor at factory joint (FJ) was jointed by welding method. The reinforcing part of FJ was made of a tape moulding joint. The cable and FJ were subjected to a coiling test with a minimum coiling diameter of 6 m, and the test was conducted three times. The cable, combined with the FJ, was then subjected to tensile bending tests three times. The tensile bending tests were conducted using a sheave with a diameter of 8 m at 134 kN. After these mechanical tests, the cable and FJ were installed in the PQ test circuit. For land joints, a pre-molded joint (RBJ) that consists of a one-piece rubber unit and a pre-fabricated joint (PJ) that can hold the cable conductor in position were developed. These joints were also subjected to a PQ test after the initial test. Two sets of outer terminations were subjected to the PQ test: one is a porcelain insulator, and the other is a polymer insulator. Fig.9 shows the layout of the PQ test, and Fig.10 shows the site where the test is being conducted. The 400 kV PQ test was performed under the test conditions that include a polarity reversal test for the LCC systems as recommended in CIGRE TB 496[4]. The test temperature was set at 90℃. Table 2 shows Pre-qualification tes ts conditions and results of 400 kV DC-XLPE cable system. The subjected sample did not breakdown during test period in Table 2. The test shown in Table 2 was completed in July 2013. This result shows the 400 kV DC-XLPE cable system, FJ, and some accessories have sufficient practical use performance.

Especially, in this PQ test, the test temperature is 90℃ and this test included polarity reversal. From these results, it was verified that a 400 kV DC-XLPE cable system can be applied to actual DC link lines at 90℃ for both the ordinary operation and polarity reversal operation.

Fig.8: 400 kV DC-XLPE Cable

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Table 1: Long term test experiences of DC-XLPE cables and accessories

Year	Rated Voltage	TB 219/496	PQ / Type	Tested Item
2001	500 kV	--- *1	Long term tests *1	Cable, FJ
2007	250 kV	Accord	Type	Cable, FJ, Outdoor terminations
2009	250 kV	Accord	PQ	Cable, FJ, Outdoor terminations
2010	250 kV	Accord	Type	Cable, FJ, Transition joint, Outdoor terminations
2011	250 kV	Accord	PQ	Cable, FJ, Transition joint, Outdoor terminations
2011	320 kV	Accord *2	Load cycling tests *2	Cable, FJ, Transition joint, Land joints, Outdoor terminations
2013	400 kV	Accord	PQ	Cable, FJ, Transition joint, Land joints, Outdoor terminations

All of the long term testing included a polarity reversal test at a maximum temperature of 90°C

*1: The equivalent life time is 40 years, which was based on the inverse power law (V^n x t = const.).

*2: Load cycling tests of the Type test for LCC system were conducted.

Table 2: Pre-qualification tests conditions and results of 400 kV DC-XLPE cable system

No	Test item and condition	Requirement TB 496	Results Judgment
1	Mechanical pre-conditioning - Coiling test (for submarine cables with FJ) Coiling Diameter: 6 m Number of coiling turns: 8 turns Number of testing times: 3 times - Tensile bending test (for submarine cables with FJ) Tension: 134 kN Number of testing times: 3 times	No outer damage	Good
2	Load cycle test (1) Applied voltage: +580 kV (1.45U_0) Temperature: 8/16 hours heating/cooling (max. 90°C)	30 cycles	Good
3	Load cycle test (2) Applied voltage: -580 kV (1.45U_0) Temperature: 8/16 hours heating/cooling (max. 90°C)	30 cycles	Good
4	Load cycle test with polarity reversals Applied voltage: +/-500 kV (1.25U_0) Polarity reversal: every 8 hours Temperature: 8/16 hours heating/cooling (max. 90°C)	20 cycles	Good
5	High load test (1) Applied voltage: +580 kV (1.45U_0) Temperature: 90°C (without heating cycle)	40 days	Good
6	High load test (2) Applied voltage: -580 kV (1.45U_0) Temperature: 90°C (without heating cycle)	40 days	Good
7	Zero load test Applied voltage: -580 kV (1.45U_0) Temperature: ambient temperature	120 days	Good
8	Load cycle test (3) Applied voltage: +580 kV (1.45U_0) Temperature: 8/16 hours heating/cooling (max. 90°C)	30 cycles	Good
9	Load cycle test (4) Applied voltage: -580 kV (1.45U_0) Temperature: 8/16 hours heating/cooling (max. 90°C)	30 cycles	Good
10	Load cycle test with polarity reversals Applied voltage: +/-500 kV (1.25U_0) Polarity reversal: every 8 hours Temperature: 8/16 hours heating/cooling (max. 90°C)	20 cycles	Good
	Total	360 days	
11	Superimposed switching impulse voltage test DC=+400 kV, SS=-480 kV, 10 times DC=-400 kV, SS=+480 kV, 10 times Conductor temperature: 90°C	No Brakdown	Good
12	Superimposed lightning impulse voltage test DC=+400 kV, LI=-840 kV, 10 times DC=-400 kV, SS=+840 kV, 10 times Conductor temperature: 90°C	No Brakdown	Good
13	Subsequent DC test Applied voltage: -580 kV (2 hours) Conductor temperature: 90°C	No Brakdown	Good

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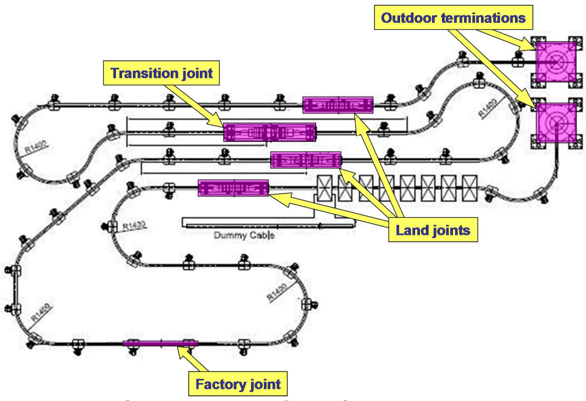

Fig.9: Layout of 400 kV PQ test

Fig.10: View of 400 kV PQ test

+/-250 kV DC-XLPE CABLE SYSTEM FOR HOKKAIDO-HONSHU DC Link

The Hokkaido-Honshu DC link was put into operation in December 2012. Fig.11 shows the location of the Hokkaido-Honshu HVDC link. The total route length between the Hakodate Converter Station in Hokkaido Is and the Kamikita Converter Station in Honshu Is is approximately 167 km. The approximately 43 km between the Furukawa Cable Head in Hokkaido Is and the Sai Cable Head in Honshu Is is the cable section. The cable section includes two land subsections and an undersea subsection; the undersea subsection length crossing the Tsugaru Straits is approximately 42 km. The power transmission capacity (bipolar) of the Hokkaido-Honshu HVDC link is 600 MW at an operating voltage of ±250 kV.

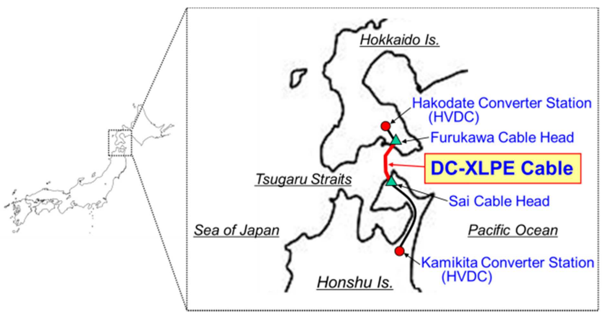

Fig.11: Route location of Hokkaido-Honshu HDDC link in JAPAN[5]

CONCLUSION

We have developed DC-XLPE insulating materials that have excellent properties for DC voltage applications. A 400 kV-class PQ test was completed under test conditions that conform to CIGRE TB 496. All the long-term demonstration testing included a polarity reversal test. They were conducted at the conductor temperature of 90℃. From this result, we verified that our DC-XLPE cable and accessories can be applied to 90℃ normal operation and polarity reversal operation in actual HVDC links.

DC power transmission technology is not only applied to the conventional long-distance and large-capacity power transmission, but is also expected to find wide applications as an environment-friendly technology that enables high efficiency power transmission in conjunction with renewable energy technologies such as off-shore wind power generation and mega-solar power generation as well as smart grid technology. As described in this paper, our DC-XLPE cable system provides a practical solution to the demand of the times. We will continue to contribute to the establishment of HVDC infrastructure around the world.

ACKNOWLEDGMENT

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